# The Carbon Footprint of Carbon Dioxide

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# Agenda

Background

Technology Descriptions

Unit Processes

Key Parameters

Co-product Management

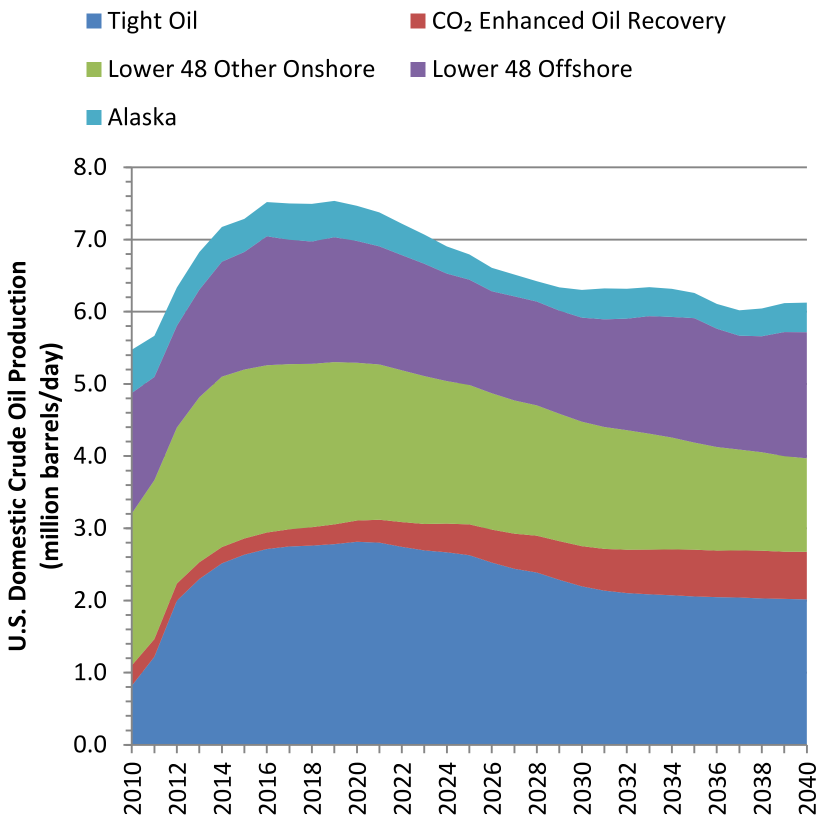
Cradle-to-Gate Results

Sensitivity and Uncertainty

Summary

# Background – Why are we studying this?
## *Enhanced Oil Recovery*

- **Enables additional recovery of crude**
- **$CO_2$ injection is alternated with injection of brine**
- **EOR produces additional crude; however, EOR also sequesters $CO_2$**
- **Increasing EOR production increases the demand for $CO_2$**
- **This presentation focuses on the options for acquiring $CO_2$ for EOR, not EOR itself (see other NETL talks)**




- EOR
  - Projected annual growth rate of 3.5% through 2040
  - 10.8% of U.S. production by 2040 (compared to 5.1 % in 2010)



*Source: EIA (2013)*

# Technology Descriptions

- **$CO_2$ from Natural Dome**
  - Reservoirs of high purity $CO_2$
  - Existing $CO_2$ domes: McElmo, Sheep Mountain, Jackson, and Bravo domes in Western U.S.
  - Recovery of $CO_2$ requires construction of a well with a carbon steel casing
  - Contains water and must be dehydrated prior to compression and pipeline transport

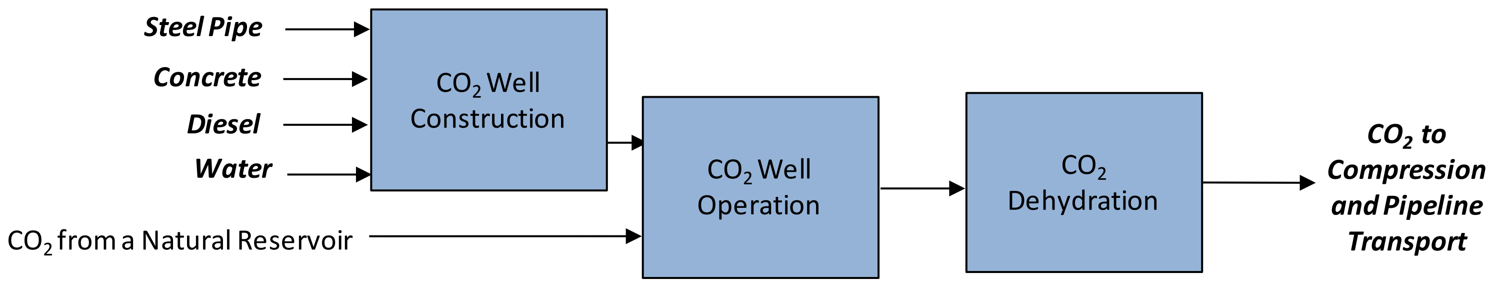
- **$CO_2$ from Natural Gas (NG) Processing**
  - Unprocessed NG contains acid gas, including variable concentrations of $CO_2$
  - NG processing increases the heating value and reduces the acid gas composition of natural gas
  - Most NG processing plants vent NG, but at some scales it may be feasible to capture $CO_2$

- **$CO_2$ from Ammonia Production**
  - $CO_2$ is a co-product of synthetic ammonia
  - Ammonia plants use natural gas as a fuel and feedstock
  - An ammonia plant has two key sources of $CO_2$
    - Emissions from *reforming*
    - Emissions from *stripping*.
  - $CO_2$ from reforming cannot be easily captured, but acid gas from stripping is 99 percent $CO_2$ and can be easily captured.

- **$CO_2$ from Captured Electricity Production**
  - $CO_2$ is a co-product of fossil power generation; consider Supercritical Pulverized Coal (SCPC), and Natural Gas Combined Cycle (NGCC) power plants

# Unit Processes for $CO_2$ from Natural Dome

- **$CO_2$ well construction**
  - Based on environmental impact statement for Kinder Morgan $CO_2$ extraction sites in Western U.S.
  - Key parameters include well depth, well life, and well production rate
  - Inputs include construction materials (steel and concrete), diesel used by drilling rig, and water used for drilling mud
- **$CO_2$ well operation accounts for fugitive $CO_2$ emissions**
  - Valve leakage and other fugitive $CO_2$ emissions are accounted for by single emission factor, adapted from NETL's existing unit processes for NG extraction
  - Existing NG emission factor was adapted according to molecular weights of methane vs. $CO_2$
- **$CO_2$ dehydration**
  - Reboiler heat and pump power provided by grid electricity instead of NG



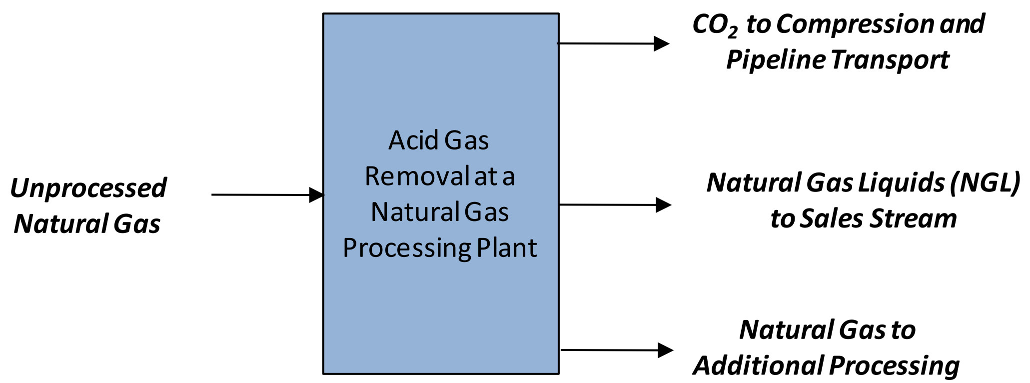
# Key Parameters for $CO_2$ from Natural Domes

| Parameter Name | Low | Expected | High | Units | Description |
|---|---|---|---|---|---|
| **$CO_2$ Well Construction** | | | | | |
| Drill speed | 1.42E+01 | 1.78E+01 | 2.13E+01 | m/h | Drilling rate |
| Drill depth | 1.00E+03 | 2.08E+03 | 2.50E+03 | m | Well depth |
| Drill power | | 4.47E-01 | | MW | Power of drilling equipment in brake specific power |
| Diesel rate | | 2.21E+02 | | kg/MWh | Use rate of diesel; kg of diesel combusted per MWh of brake drilling energy |
| Total casing mass | | 1.03E+05 | | kg/well | Total mass of carbon steel well casing |
| Total concrete mass | | 1.11E+05 | | kg/well | Total mass of concrete well casing |
| Groundwater proportion | | 5.00E-01 | | dimensionless | Fraction of groundwater used during drilling |
| Surface water proportion | | 5.00E-01 | | dimensionless | Fraction of surface water used during drilling |
| Fresh water mass | | 6.65E+05 | | kg/well | Fresh water demand for drilling |
| Brine water mass | | 3.11E+05 | | kg/well | Brine water demand for drilling |
| **$CO_2$ Well Operation** | | | | | |
| Fugitive $CO_2$ | | 4.64E-06 | | kg/kg | Fugitive loss of $CO_2$ from valves, per kg of $CO_2$ extracted |
| Well life | 20 | 25 | 30 | years | Production life of a $CO_2$ well, used to calculate share of well construction per unit of $CO_2$ dehydrated |
| $CO_2$ production rate | 5.66E+05 | 8.09E+05 | 1.05E+06 | kg/well-day | Production rate of a $CO_2$ well, used to calculate share of well construction per unit of $CO_2$ dehydrated |
| Well success rate | 0.65 | 0.70 | 0.85 | dimensionless | Fraction of wells drilled that have economically viable production rates, used to calculate share of well construction per unit of $CO_2$ dehydrated |
| **$CO_2$ Dehydration** | | | | | |
| $CO_2$ loss | | 1.15E-04 | | kg/kg $CO_2$ | $CO_2$ emissions released to air during glycol regeneration, in terms of $CO_2$ treated |
| Dehydration Power | | 1.93E-04 | | kWh/kg $CO_2$ | Electricity requirements for pumping and heating glycol used for dehydration, in terms of $CO_2$ treated |

- Well construction and operation parameters based on discussions with representatives of Kinder Morgan and comparisons between NG and $CO_2$ well practices
- Dehydration parameters based on comparisons between NG and natural $CO_2$ compositions

# Unit Process for $CO_2$ from NG Processing

- **Based on acid gas removal (from NETL's NG model)**
  - Unlike existing NG model, $CO_2$ is captured instead of vented
  - Processed NG is sent to additional processing steps that are not necessary for $CO_2$
- **Parameters are used to account for variable $CO_2$ concentrations**
  - Production gas contains 1.5 to 80+ percent (by mass) $CO_2$
  - There are four existing sites that capture $CO_2$ from NG processing for purposes of EOR
  - This model uses the composition of gas from those facilities (76.9 to 81.1 percent) as the basis of the analysis, since low compositions cannot be economically captured
  - Reference flow of unit process is 1 kg of captured $CO_2$, so energy and material flows scale according to incoming $CO_2$ concentration



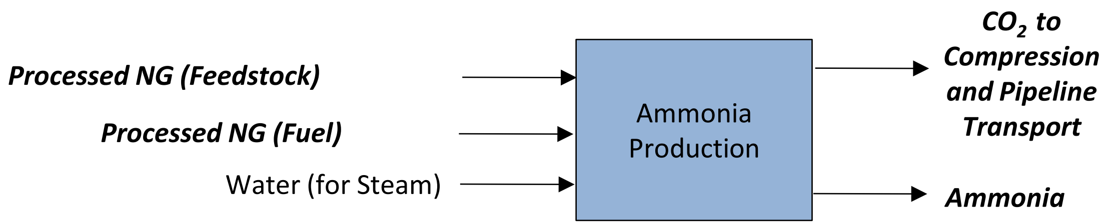
# Key Parameters for $CO_2$ from NG Processing

| Parameter Name | Low | Expected | High | Units | Description |
|---|---|---|---|---|---|
| Solvent makeup rate | 9.98E-05 | 1.00E-04 | 1.01E-04 | kg/kg $CO_2$ captured | Makeup rate of amine solvent for $CO_2$ recovery, in kg of solvent per kg of $CO_2$ captured |
| NG fuel | 6.33E-02 | 6.64E-02 | 6.95E-02 | kg/kg $CO_2$ captured | Combusted NG input for steam generation per unit of $CO_2$ captured |
| Water input | 1.48E-02 | 1.49E-02 | 1.50E-02 | kg/kg $CO_2$ captured | Water withdrawal per unit of $CO_2$ captured |
| Surface water share | 0.00E+00 | 5.00E-01 | 1.00E+00 | dimensionless | Share of water withdrawn from surface water sources |
| $CO_2$ input composition | 0.8113 | 0.7882 | 0.7690 | dimensionless | $CO_2$ fraction of incoming stream |
| $H_2S$ input composition | | 5.00E-03 | | dimensionless | $H_2S$ fraction of incoming stream |
| NGL input composition | | 1.50E-01 | | dimensionless | NG liquids (NGL) fraction of incoming stream |
| $CO_2$ pipeline composition | | 4.70E-03 | | dimensionless | $CO_2$ fraction of pipeline NG, used to calculate amount of $CO_2$ removed during processing |
| $H_2S$ removal rate | | 9.80E-01 | | dimensionless | Removal rate of $H_2S$ |

- Solvent makeup and NG fuel rates based on variability shown by data sources (FLUOR, 2003; NETL, 2010; NETL, 2011)
- $CO_2$ composition in incoming gas (i.e., “production gas”) based on characteristics of NG wells that capture $CO_2$ for use in EOR in the Permian Basin
- $CO_2$ removal rate is a dependent variable, calculated based production gas composition (variable) and pipeline gas composition (0.47% mass $CO_2$) (NETL, 2012)

# Unit Process for $CO_2$ from Ammonia Production

- **NG is feedstock and fuel (coal is a negligible share of ammonia feedstock in the U.S.)**
- **Ammonia production is a two-step process**
  - Step 1: Steam reforming of NG to produce carbon monoxide (CO) and hydrogen ($H_2$)
  - Step 2: Catalyzed conversion of hydrogen and nitrogen to ammonia
- **Instead of being used for urea production, $CO_2$ is sent to carbon capture, utilization and storage (CCUS)**
- **Key data sources**
  - Energy and feedstock profiles by government-sponsored research (Energetics, 2000; USDA, 2007; Worrell et al., 2000)
  - EPA emission factors for ammonia plants (EPA, 2009)
  - Water use data from European fertilizer industry (EFMA, 2000)



# Key Parameters for $CO_2$ from Ammonia Production

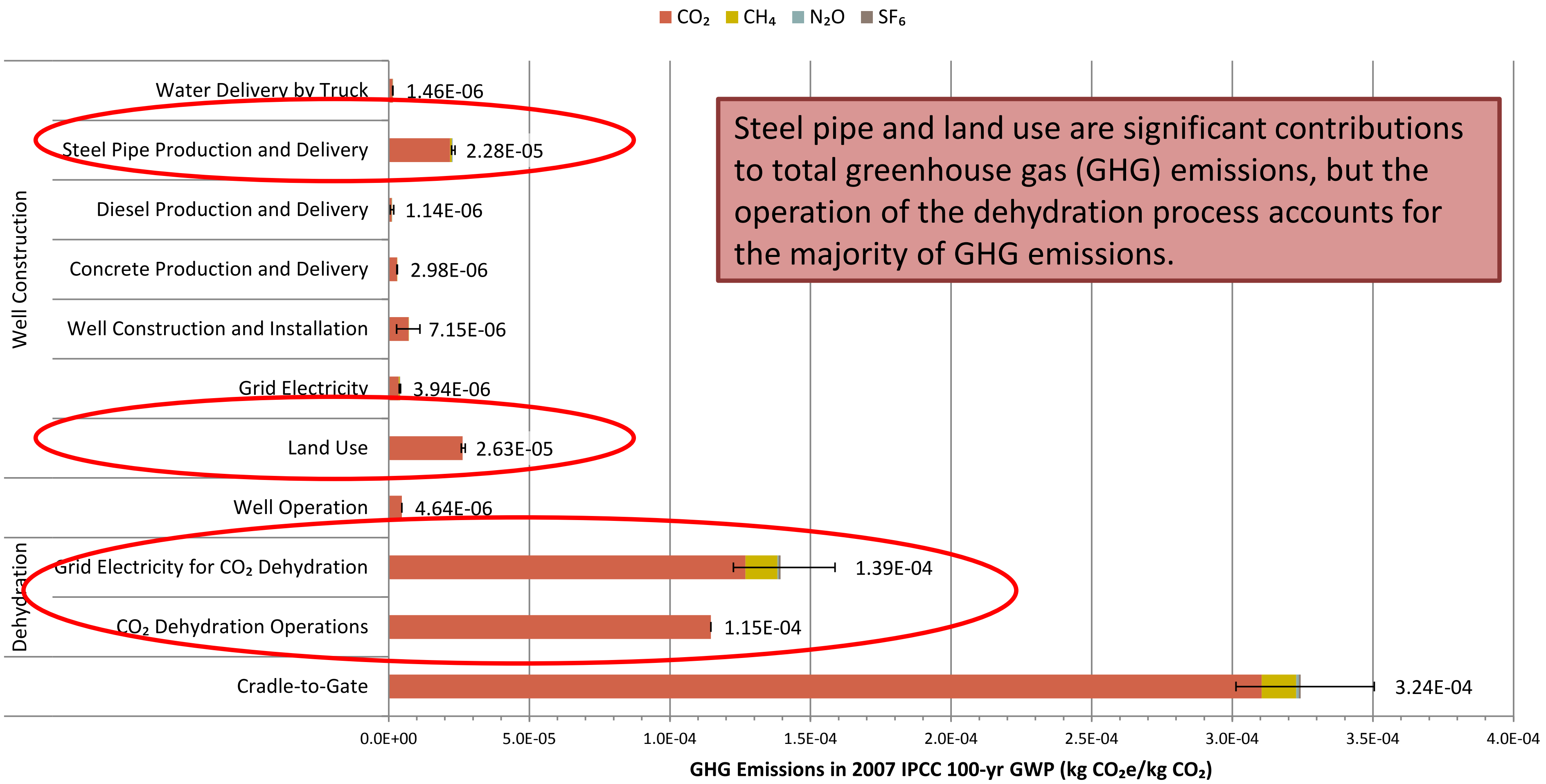
| Parameter Name | Low | Expected | High | Units | Description |
|---|---|---|---|---|---|
| NG input | 7.78E-01 | 9.30E-01 | 1.08E+00 | kg/kg $CO_2$ captured | NG input (feedstock and fuel) per unit of $CO_2$ captured |
| Water input | 1.10 | 1.72 | 2.35 | kg/kg $CO_2$ captured | Water input per unit of $CO_2$ captured |
| Fuel fraction | 3.79E-01 | 4.21E-01 | 4.64E-01 | dimensionless | Fraction of NG input used for fuel instead of feedstock |

- **Total NG input is variable**
  - Reformer efficiency affects amount of NG required for synthesis gas production
  - Intermediate reactions that shift CO to $CO_2$ also affect amount of NG feedstock
  - Extent of heat exchange between ammonia and urea production affects amount of NG required for fuel
- **Water input is also variable**
  - Majority of water input is consumed for steam generation
  - Steam requirements depend on reformer efficiency
- **$CO_2$ production rate is also variable, but is accounted for in the NG and water input parameters**
- **Data limitations prevent parameterization of flows within ammonia plant**

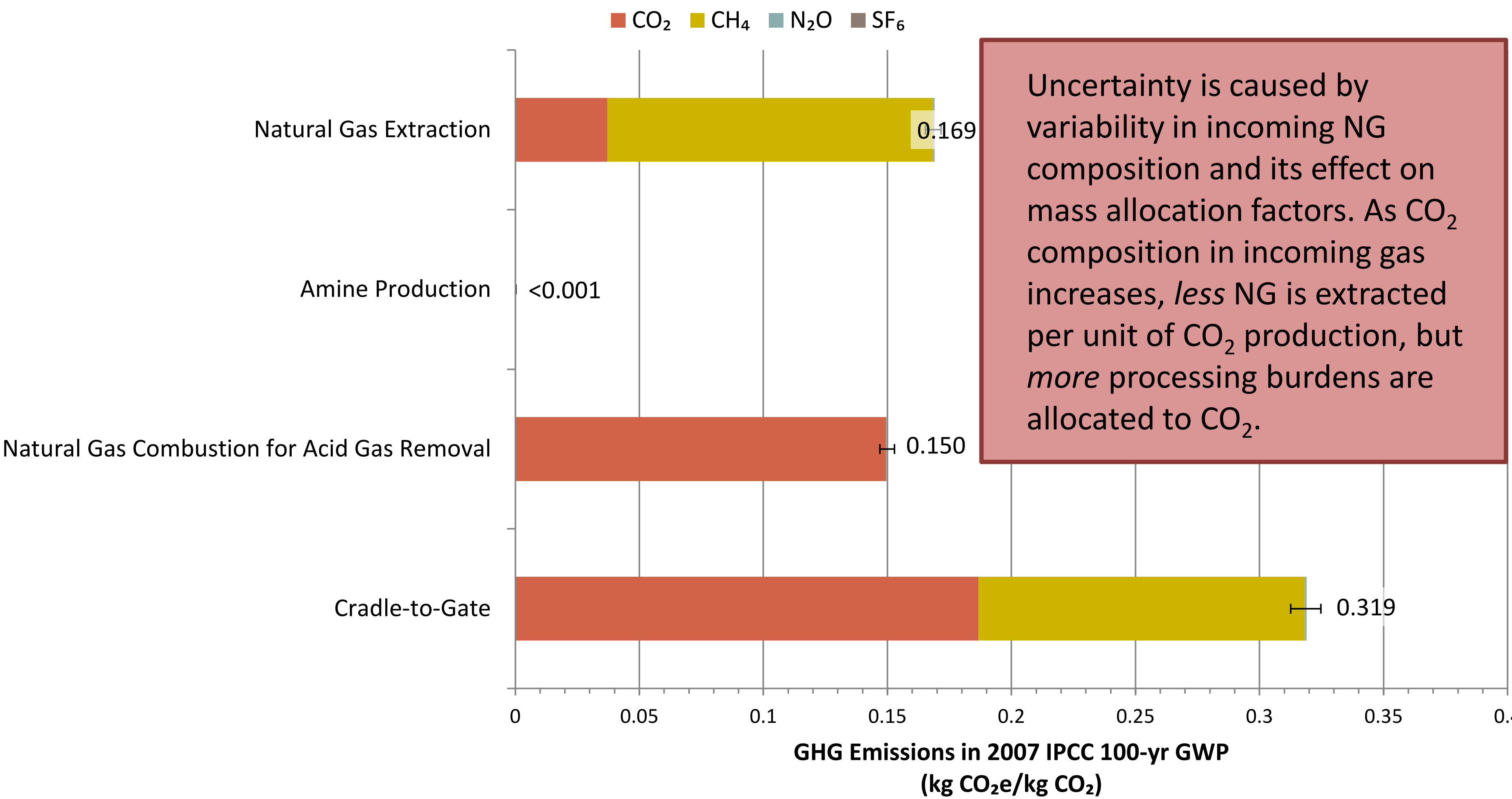
# Co-Product Management

- **Natural $CO_2$ dome produces only $CO_2$ (no co-products)**
- **NG processing produces $CO_2$, NG, and NGL**
  - $CO_2$ cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced $CO_2$ and NG
  - System expansion is also feasible, but requires consequential assumptions
- **Ammonia plant produces $CO_2$ and ammonia**
  - $CO_2$ cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced $CO_2$ and ammonia
  - System expansion is also feasible, but requires consequential assumptions
- **Coal and NG power plants produce $CO_2$ and electricity**
  - $CO_2$ cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible; nor can electricity be expressed in terms of mass
  - System expansion is the only option

# Cradle-to-Gate Results for $CO_2$ from Natural Dome

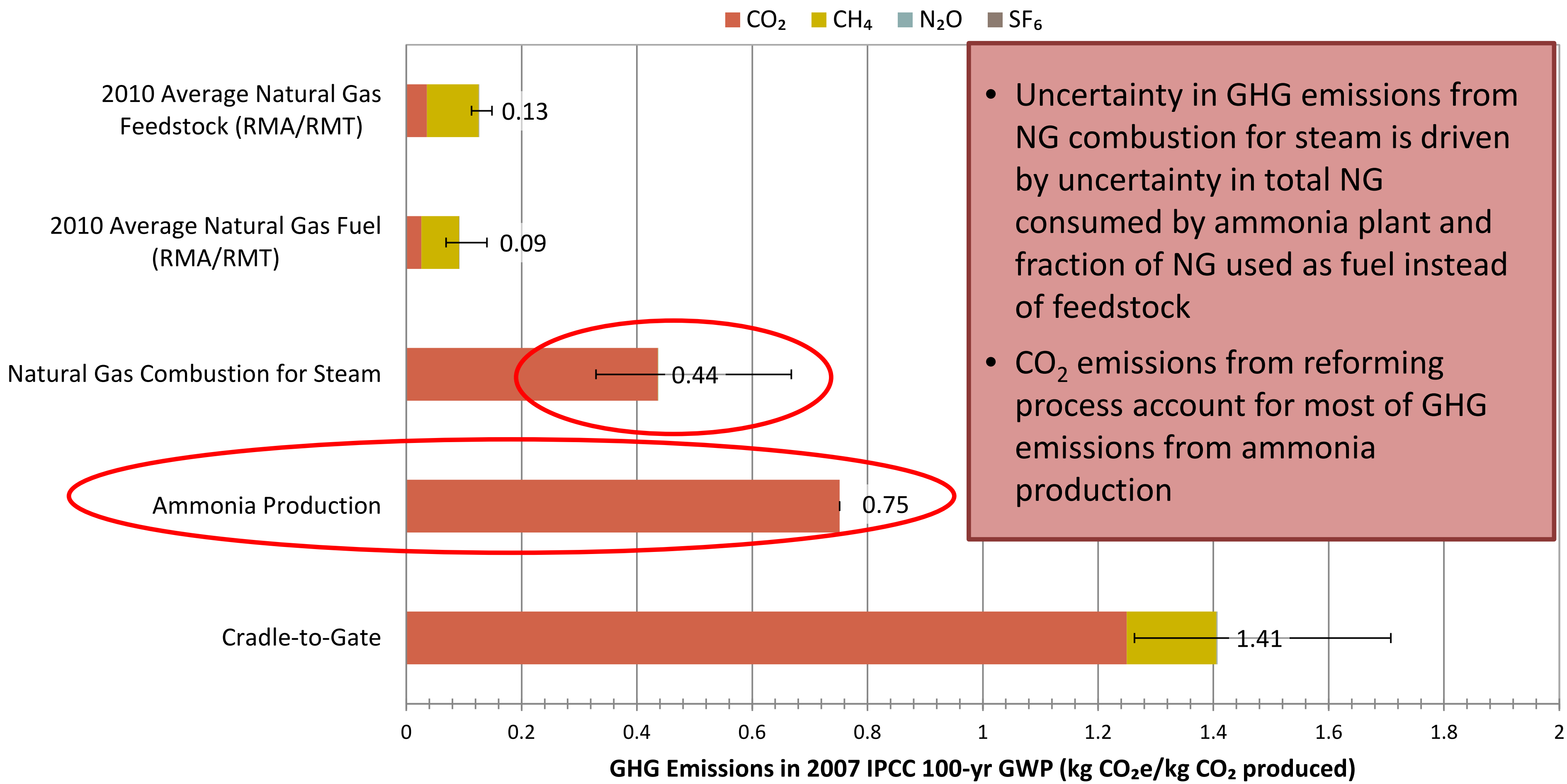


# Cradle-to-Gate Results for $CO_2$ from NG Processing (Mass Allocation)



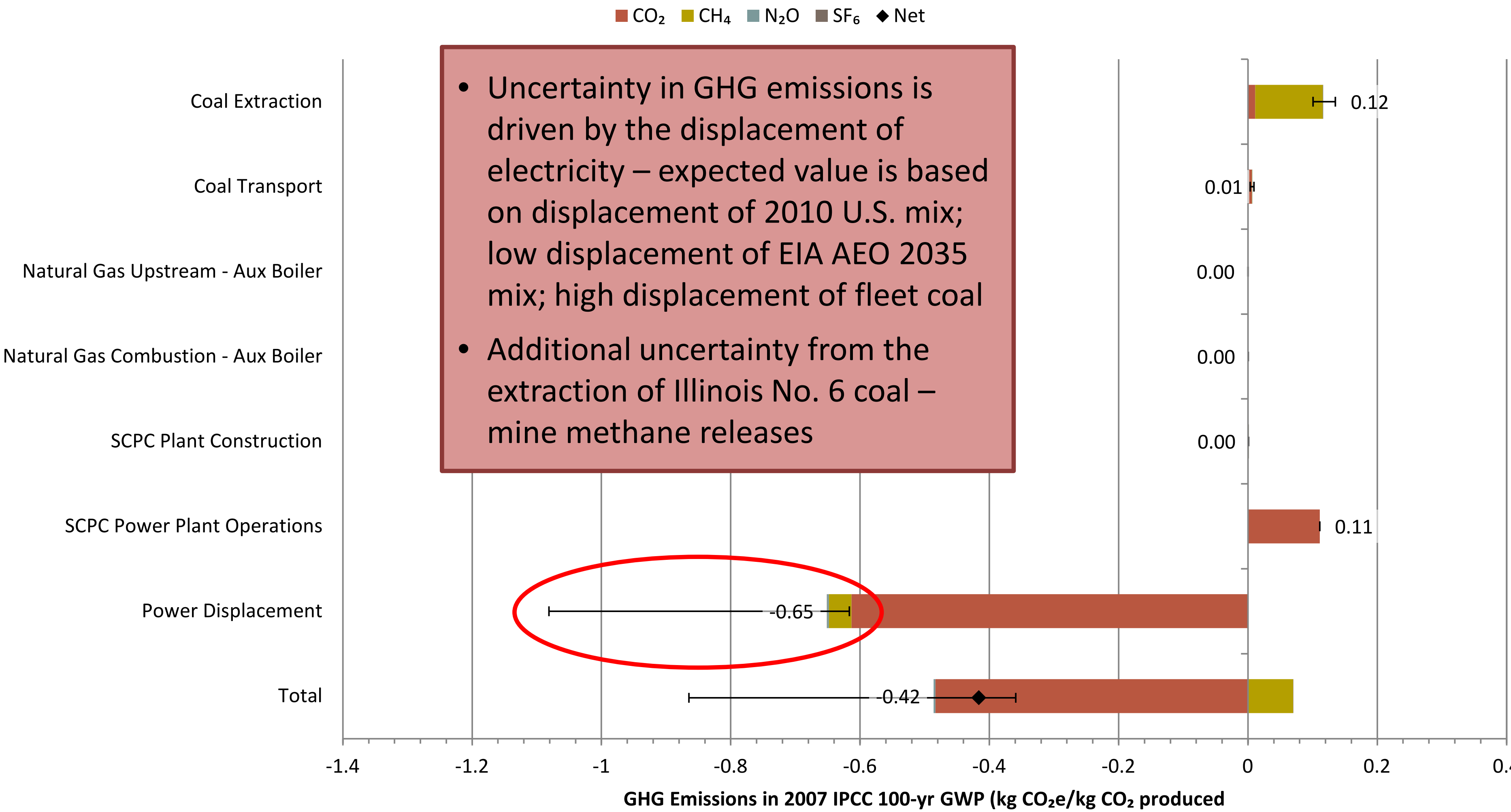

Uncertainty is caused by variability in incoming NG composition and its effect on mass allocation factors. As $CO_2$ composition in incoming gas increases, *less* NG is extracted per unit of $CO_2$ production, but *more* processing burdens are allocated to $CO_2$.

# Cradle-to-Gate Results for $CO_2$ from Ammonia Production (Mass Allocation)



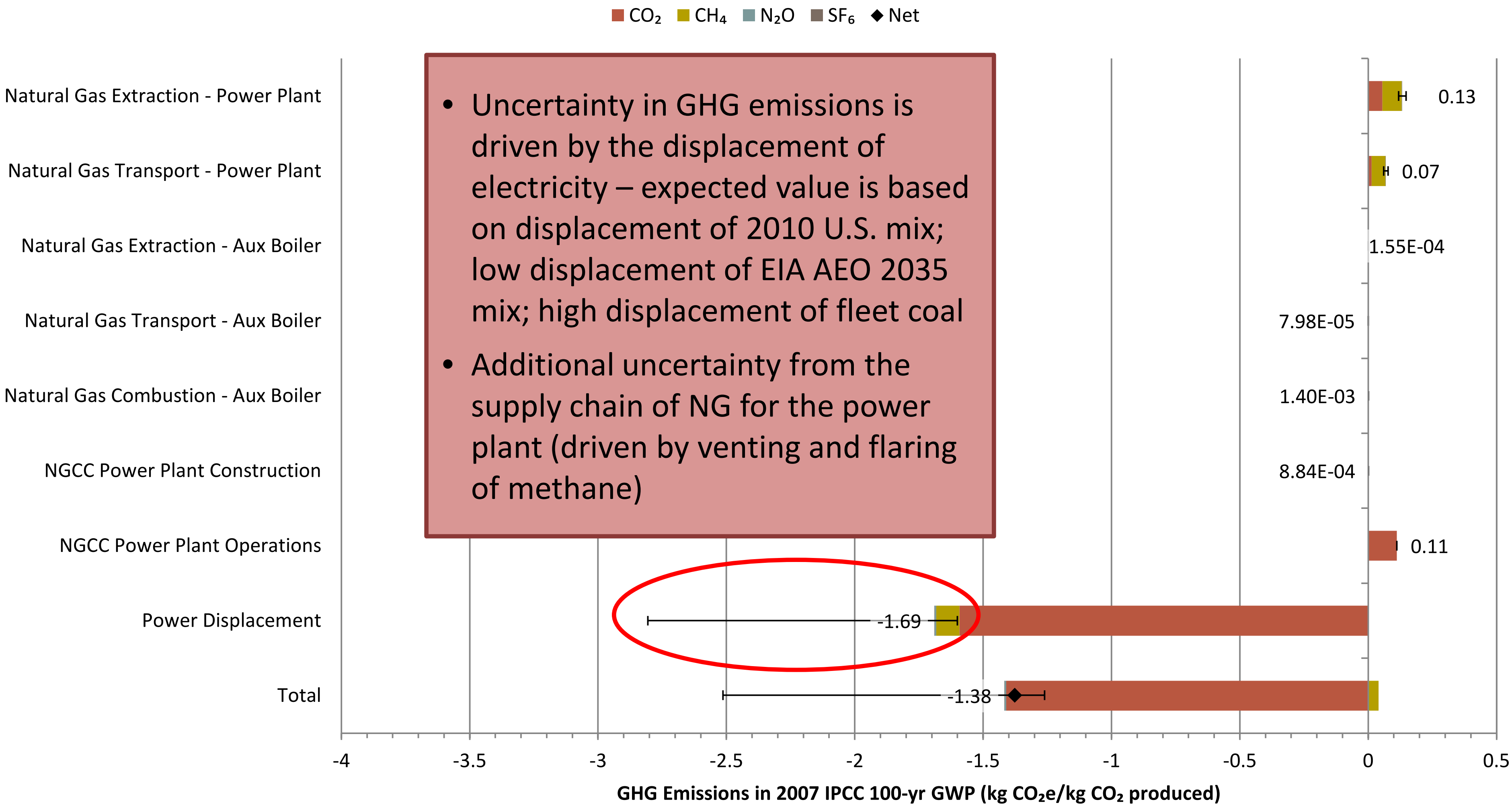

- Uncertainty in GHG emissions from NG combustion for steam is driven by uncertainty in total NG consumed by ammonia plant and fraction of NG used as fuel instead of feedstock
- $CO_2$ emissions from reforming process account for most of GHG emissions from ammonia production

# Cradle-to-Gate Results for $CO_2$ from SCPC Power Plant (Displacement)



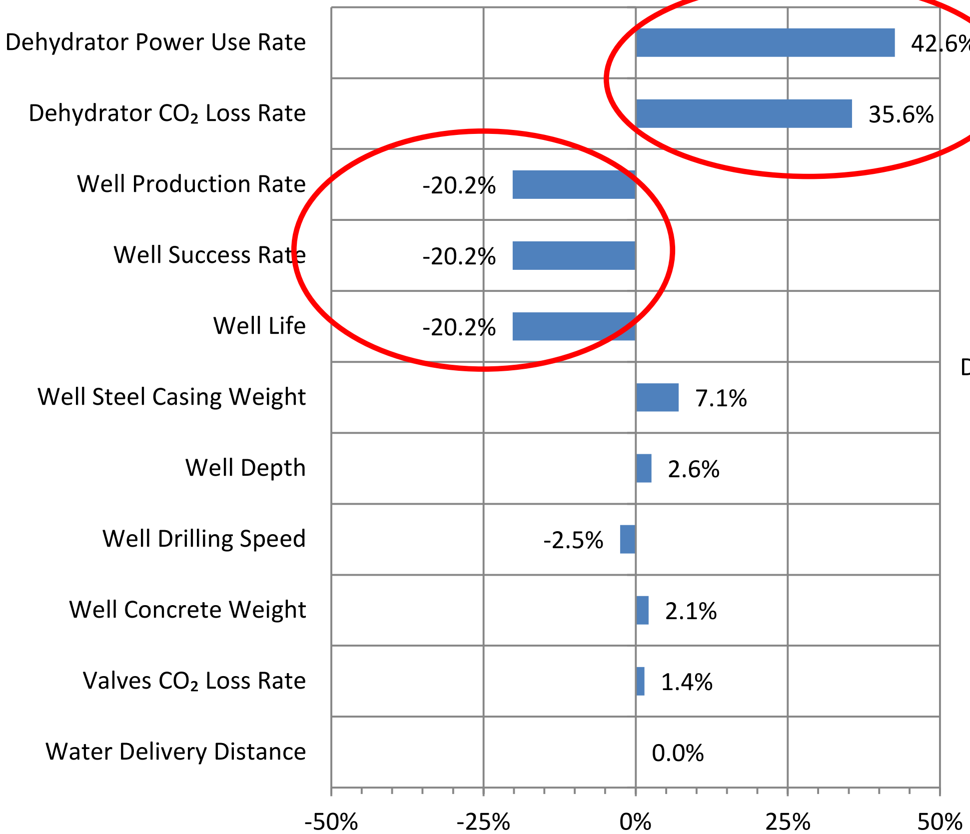

- Uncertainty in GHG emissions is driven by the displacement of electricity – expected value is based on displacement of 2010 U.S. mix; low displacement of EIA AEO 2035 mix; high displacement of fleet coal
- Additional uncertainty from the extraction of Illinois No. 6 coal – mine methane releases

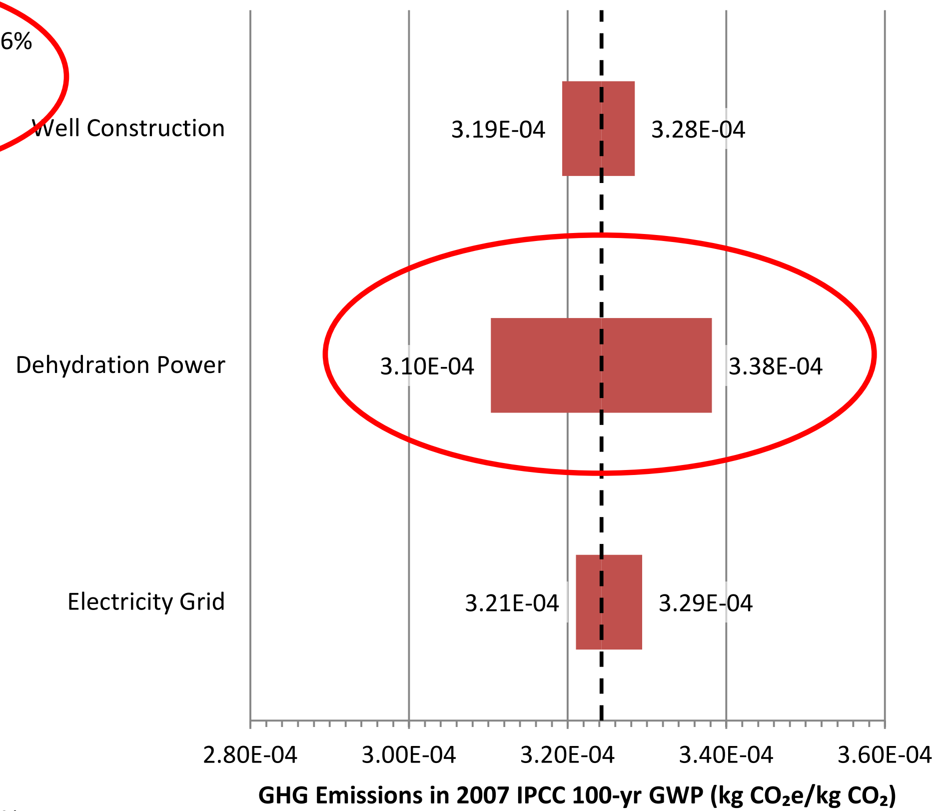
# Cradle-to-Gate Results for $CO_2$ from NGCC Power Plant (Displacement)




- Uncertainty in GHG emissions is driven by the displacement of electricity – expected value is based on displacement of 2010 U.S. mix; low displacement of EIA AEO 2035 mix; high displacement of fleet coal
- Additional uncertainty from the supply chain of NG for the power plant (driven by venting and flaring of methane)

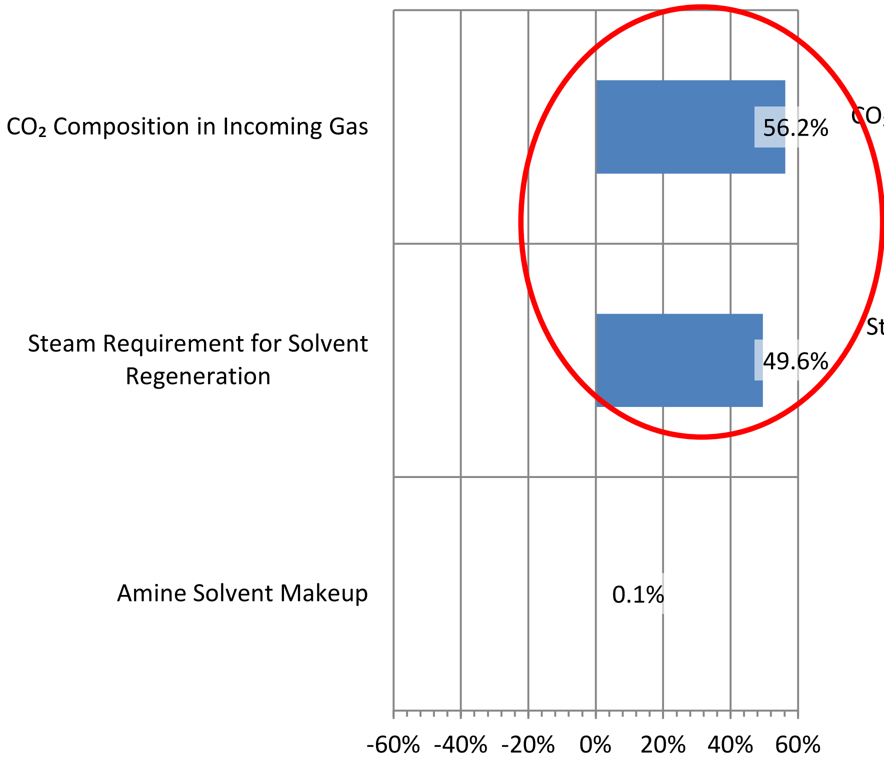
# GHG Sensitivity and Uncertainty for $CO_2$ from a Natural Dome

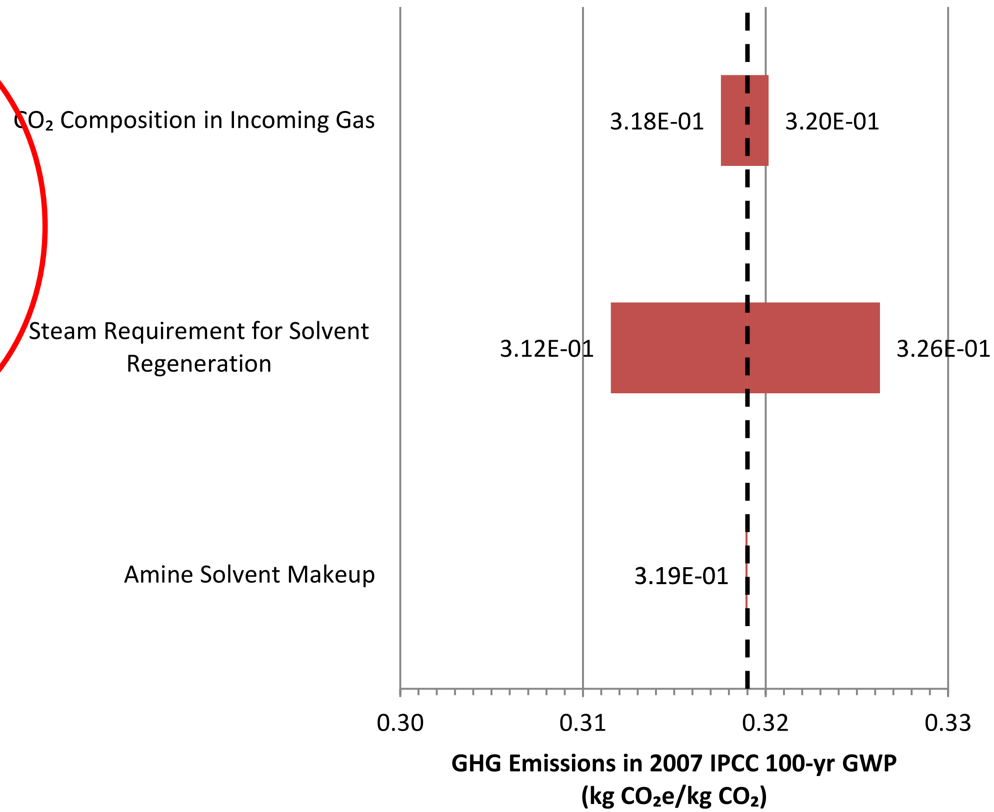



- GHG results are sensitive to changes in dehydrator variables (power use and $CO_2$ loss rate)
- GHG results show an inverse relationship to well production rate, well success rate, and well life – these parameters affect denominator used for apportioning construction and land use burdens
- Greatest uncertainty in GHG results is caused by uncertainty in $CO_2$ processing (dehydration)

# GHG Sensitivity and Uncertainty for $CO_2$ from NG Processing




- GHG emissions sensitive to changes in $CO_2$ composition of incoming gas and steam rates for gas processing



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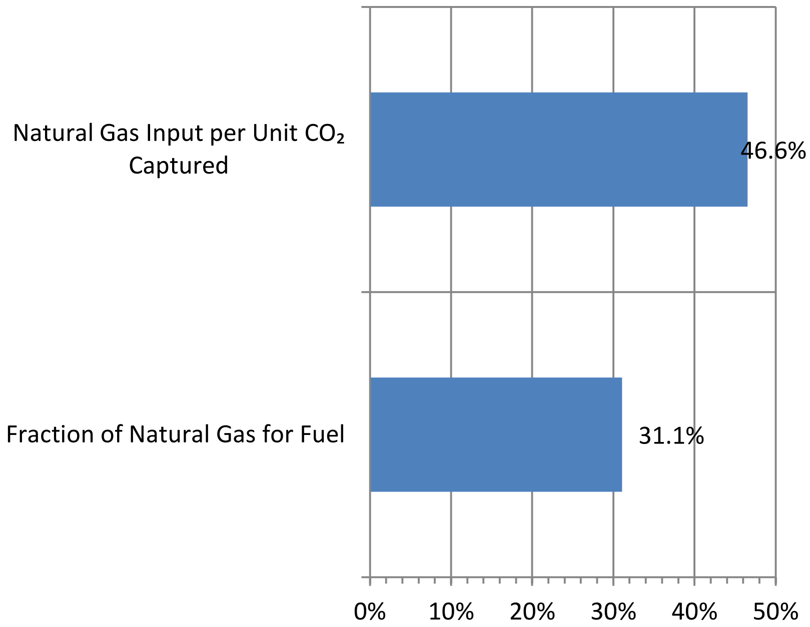
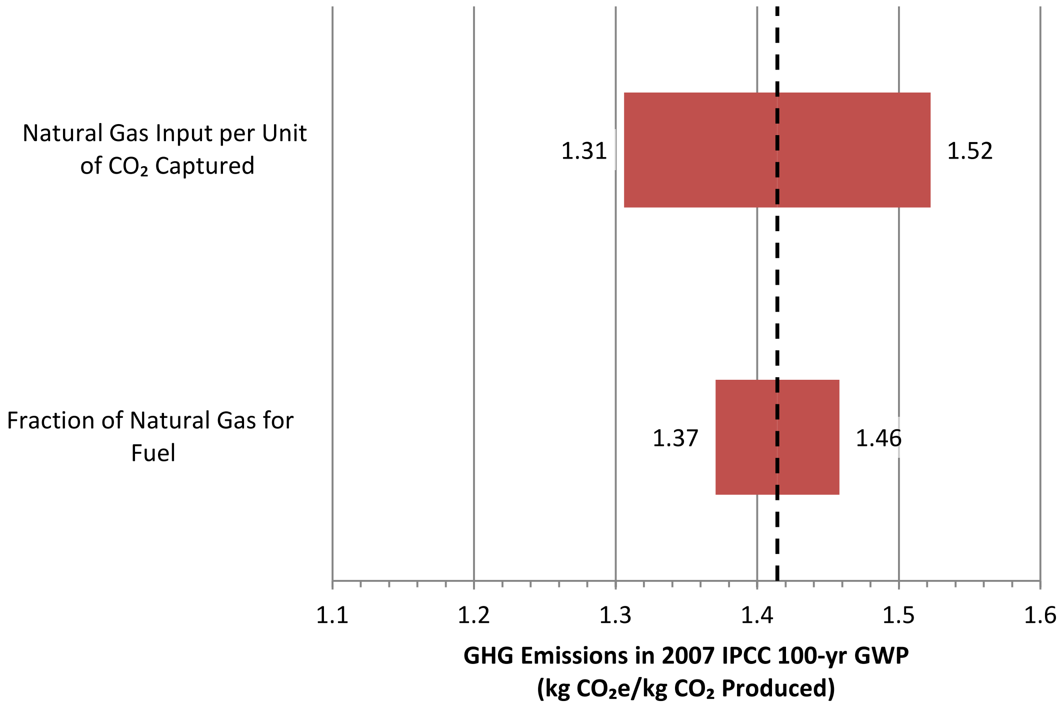
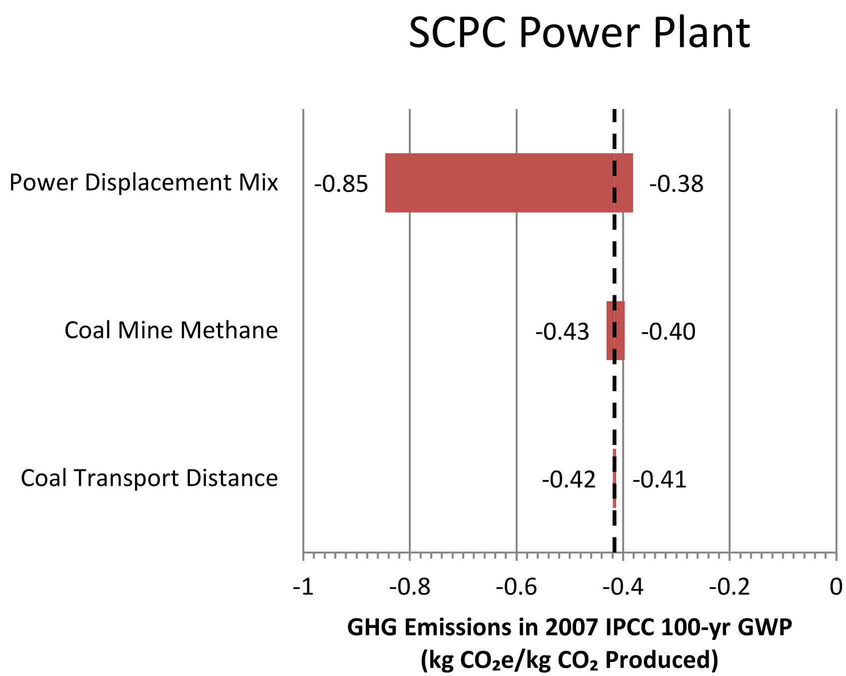
# GHG Sensitivity and Uncertainty for $CO_2$ from Ammonia Production

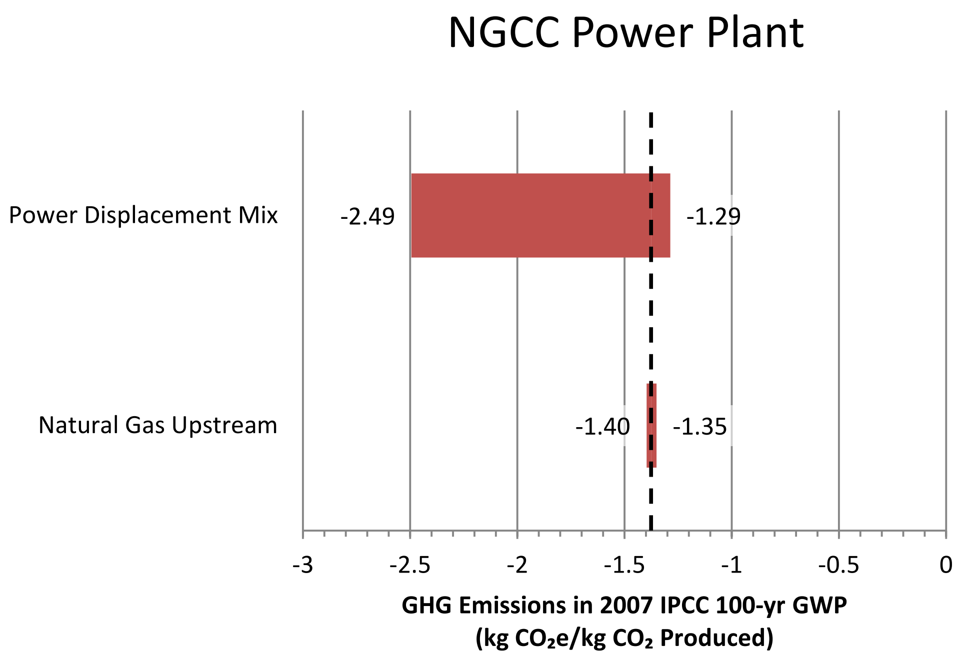



- Due to the high GHG footprint of NG extraction, GHG emission sensitivity *and* uncertainty driven by NG input rate
- Data limitations prevent parameterization of other ammonia plant operating characteristics

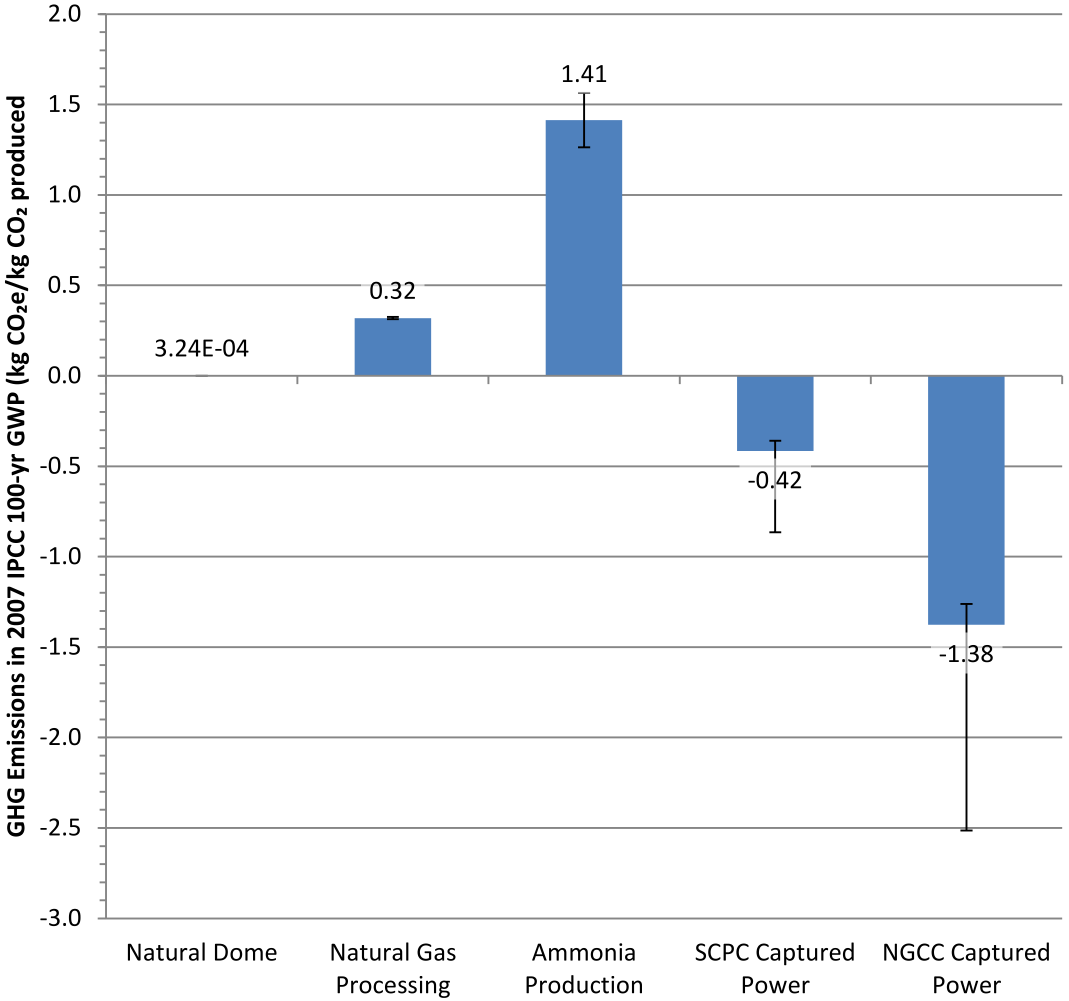
# GHG Uncertainty for $CO_2$ from SCPC and NGCC Power Plants




- For both technologies, majority of uncertainty in GHG emissions is driven by the displacement of electricity – expected value is based on displacement of 2010 U.S. mix; low displacement of EIA AEO 2035 mix; high displacement of fleet coal
- Additional uncertainty from the extraction of Illinois No. 6 coal – mine methane releases for SCPC
- Additional uncertainty from the supply chain of NG for the power plant (driven by venting and flaring of methane) for NGCC

# Carbon Footprint of $CO_2$ Summary




- Captured power values yield negative results because of the displacement of the co-product (electricity) with a more GHG-intensive conventional source (U.S. grid mix)
- Natural Dome has effectively zero environmental burden – the resource is extracted directly, no conversion processes necessary’
- Alternative sources for captured $CO_2$ (NG processing and Ammonia production) are less GHG-efficient methods because of the processing emissions

# Recommendations and Conclusions

- Above results are only from cradle to gate, so they should be used with care
- These models allow further LCA modeling of carbon capture, utilization, and storage (CCUS) scenarios
- A detailed report on these models is currently under review and will be released soon on the NETL Energy Analysis site
- For more information on EOR, consider attending these NETL presentations in the “Fossil Fuels 2” session from 3:00-4:30 in Ligurian II:
  - A Parameterized Life Cycle Model of Crude from $CO_2$-Enhanced Oil Recovery
  - The Challenge of Co-product Accounting for Large-scale Energy Systems: Power, Fuel and $CO_2$

# Contact Information



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